

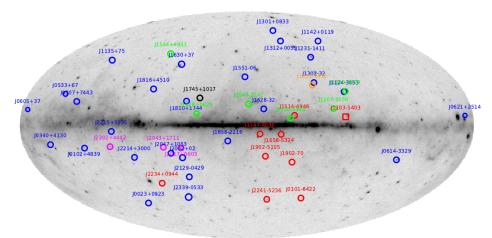
NASA AND NANOHERTZ GRAVITATIONAL WAVE ASTRONOMY

North American Nanohertz Observatory for Gravitational Waves (NANOGrav)

The direct detection and subsequent exploitation of gravitational waves (GWs) as a non-photonic probe of the Universe will almost certainly occur by the end of the current decade in two dramatically different frequency bands. Advanced LIGO will detect and study GWs in the kHz regime, while NANOGrav and the other pulsar timing arrays (PTAs) making up the International Pulsar Timing Array will detect and study those at nHz frequencies, most likely initially from supermassive ($10^8-10^{10} \, \mathrm{M}_{\odot}$) black hole binaries in the nearby Universe.

NANOGrav looks for correlated timing signals in high-precision pulse arrival measurements from an ensemble of radio millisecond pulsars (MSPs) scattered about the sky. Current GW sensitivity is limited by the number of known "good" MSPs, but systematic timing effects will almost certainly become important as timing precision continues to improve (primarily thanks to new radio instrumentation and timing techniques). Future NASA missions, if they include appropriate capabilities, can both directly and indirectly address these issues.

• A future γ-ray mission, with greater 100–3000 MeV sensitivity than *Fermi*, could guide radio surveys to many new MSPs, extending *Fermi*'s surprising and fantastic results—this Figure highlights 45 new *Fermi*-directed radio MSP discoveries, many now in use by PTAs.



- An Explorer-class X-ray timing mission could provide high-precision timing of many MSPs with no detrimental effects (i.e., dispersion and scattering) from the ISM, directly contributing PTA data and providing calibration for ISM mitigation strategies in the radio.
- Next-generation astrometry missions (à la *Gaia*) could yield distances to nearby binary MSPs to sub-pc accuracy, enabling us to analyze our pulsar timing data *coherently*, potentially leading to a factor of two improvement in sensitivity as well as much better localization of GW sources for multiwavelength follow-up.
- A sensitive low-frequency radio telescope on the Moon could directly monitor ISM variations toward many MSPs with unprecedented precision, directly improving radio timing.
- High-sensitivity X-ray timing and spectroscopy of MSPs could directly determine neutron star masses and radii, potentially reducing parameter covariances with GW signals.
- Improvements in Solar System ephemerides via tracking of deep-space NASA missions will enhance pulsar timing on long timescales, those most important for nHz GW astronomy.

Thus, future NASA missions can substantially improve GW measurements in the coming decades, whether or not NASA participates in a dedicated GW space mission.